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REVIEW

Prediction of Self-Compacting Concrete homogeneity by ultrasonic velocity

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KEYWORDS

Ultrasonic;
Velocity;
Transmission;
Homogeneity;
Sieve stability;
Segregation

Abstract To evaluate the filling capacity of self-compacting concrete SCC without segregation, a technique based on the ultrasonic velocity has been adapted in order to estimate homogeneity and quality of concrete at very young age.

To monitor local change in ultrasonic velocity, the process consists of using a pair of transducers at different depths of the concrete. The aim of our experimental study was to establish the relationship between ultrasonic velocity measured by sensors of 50 mm diameter and of 54 kHz frequency, and homogeneity of fresh concrete. Measurements of wave propagation velocity are carried out every half an hour on a vertical channel whose dimensions (in mm) are 160 × 160 × 700. These measurements have been determined with three modes of transmission: direct, semi-direct and indirect. The different mixtures were prepared with the same Water/Binder ratio (W/B) of 0.28. The amount of binder is in the order of 520 kg/m^3.

Comparison between ultrasonic velocity and empirical tests such as sieve stability test, slump flow test, air content, and compressive strength, at 1 day, shows that the ultrasonic velocity can also be very useful to evaluate homogeneity and quality of fresh concrete.

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1. Introduction

Static segregation process appears when coarse aggregate separates from the paste and settles down when the concrete is in plastic state after casting [1]. Because the grains of different sizes behave differently, the segregation can occur further to any mixture movement. If the water content exceeds certain value, the frictions decrease and it occurs a separation by sedimentation. Thus, the coarse grains settle rapidly, while fines are swept away by the water (Fig. 1). On the other hand, in the case of high cohesive concrete mixtures, such as those containing silica fume or VMA, even in the absence of external bleed water, static segregation can still take place [2,3]. However, to develop fundamental understanding of concrete stability, there is a few tools that can enable the generation of real-time data on the kinetics of bleeding [3,4].

The coarse aggregate segregation can lead, with direct impact on mechanical, transport properties, and durability, to heterogeneous properties of the hardened concrete. Therefore, to achieve adequate mechanical properties and structural performance, the control of segregation is critical for the material [5–9,2,3]. Stability of fresh concrete is largely dependent on the mixture composition and kinetic of cement hydration at early age. The latter is greatly influenced by the supplementary cementitious materials [8–11,2,4].

In addition, the disadvantages resulting from the concrete segregation are as follows: (1) low and irregular strength; (2) gravel nests, permeable to air and water and allowing the corrosion of reinforcement; (3) porous regions by accumulation of fine particles; (4) irregular surface, etc.

For fresh concrete, segregation may occur in the following cases: (1) incorrect granulometric composition of the aggregates; (2) use of large quantities of water and/or admixture (superplasticizer); (3) transport; (4) implementation; (5) intense compaction, etc.

During the first hours after the implementation, the microstructure of fresh concrete remains very fragile. Unlike conventional testing methods, the ultrasonic waves do not significantly affect the microstructure. Methods using the wave propagation and interaction with the concrete are among the methods having the most potential for the non-destructive evaluation of concrete [12–15]. The ultrasonic velocity method applied to concrete is complex because it comprises various coupled phenomena: porosity, heterogeneities of different types (cement, sand, aggregates, superplasticizer...) with dimensions ranging from nanometers to centimeters.

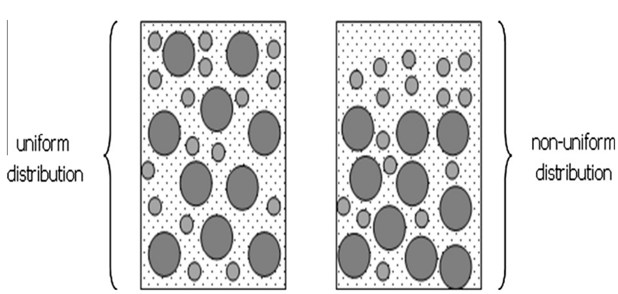


Figure 1 Schematic representation of segregation by sedimentation.

Taking into consideration the effect of superplasticizers, the main objective of this study is to evaluate the applicability of the ultrasonic velocity test to assess, using relatively large samples, the segregation of SCC and to correlate the non-destructive method results to empirical testing such as sieve stability test, slump flow test and air content, and the destructive method results to compressive strength at 1 day. The test method is based on transducers measurements that consist in the monitoring, throughout a concrete column measuring 700 mm in height as a function of time, of ultrasonic velocity differences. The variations in ultrasonic velocities are used to derive indices that reflect stability of concrete and interpret the material homogeneity. The stability deduced from the non-destructive ultrasonic velocity method is compared to the stability indices determined by empirical testing.

2. Experimental program

2.1. Materials

An ordinary Portland cement (CEM I 52.5 R), according to European Standard EN 197-1, is used in all compositions. In this study, Silica fume (SF) Sikacrete HD and Limestone Filler (LF) are used in order to modify viscosity. The superplasticizer (SP) is a polycarboxylate type based admixture, commercially branded as TEMPO 16, according to European Standard NF EN 934-2. The chemical composition and physical properties of Portland cement and mineral admixtures are given in Table 1.

Table 1 Chemical and physical proprieties of the used materials.

	CEM	LF	SF	SP
C_3S (%)	67	–	–	–
C_2S (%)	12	–	–	–
C_4AF (%)	9	–	–	–
C_3A (%)	9	–	–	–
S_iO_2 (%)	20.5	–	85	–
Fe_2O_3 (%)	2.6	0.04	–	–
Al_2O_3 (%)	5.0	<0.4	–	–
CaO (%)	65.0	–	1.0	–
MgO (%)	1.1	–	–	–
SO_3 (%)	3.6	–	2.0	–
Loss on ignition (%)	1.2	43.10	4.0	–
NaO_2 eq. (%)	0.43	–	1.0	<1.5
cl^-	0.01	–	<0.1	<0.1
Density	3.15	2.70	2.24	1.055
Blaine (cm^2/g)	4750	5550	2200	–
pH	–	–	–	3
Dry extract (%)	–	–	–	24

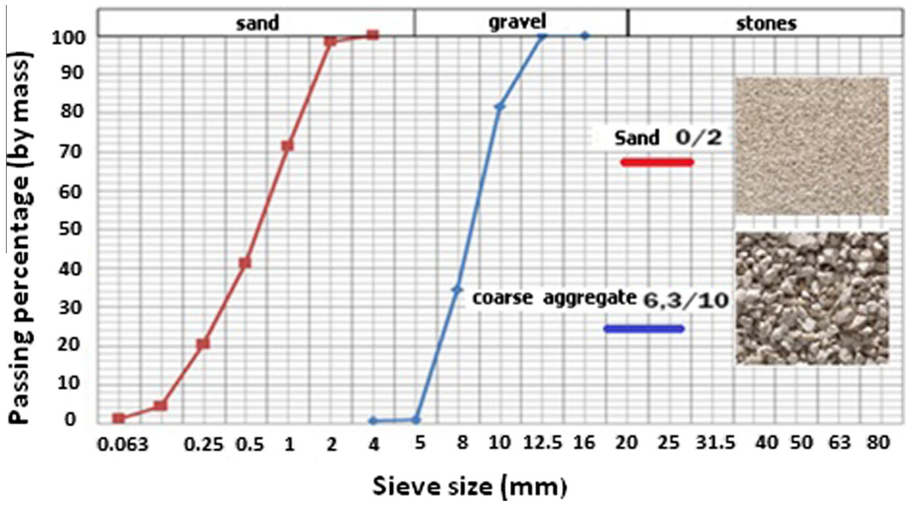


Figure 2 Particle size distribution of sand and coarse aggregate.

Table 2 Mixture proportions.

Mixture	SCC1	SCC2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8	SCC9	SCC10
Cement (kg/m^3)	350	350	350	350	350	350	350	315	315	315
LF (kg/m^3)	170	170	170	170	170	170	170	170	170	170
SF (kg/m^3)	–	–	–	–	–	–	–	35	35	35
Total cementitious materials (kg/m^3)	520	520	520	520	520	520	520	520	520	520
Total water (kg/m^3)	147	147	147	147	147	147	147	147	147	147
W/B	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Sand (0–2 mm) (kg/m^3)	890	890	890	890	890	890	890	890	890	890
Coarse aggregate (6.3–10 mm) (kg/m^3)	900	900	900	900	900	900	900	900	900	900
SP (kg/m^3)	4.87	9.75	13	15.17	17.33	19.5	21.67	17.33	19.5	21.67

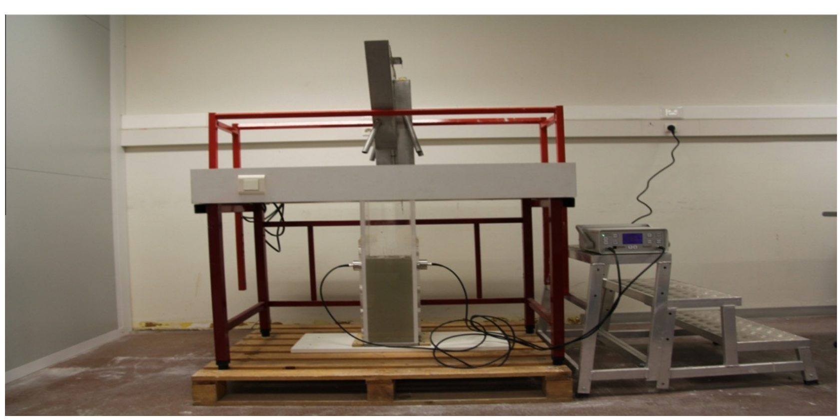
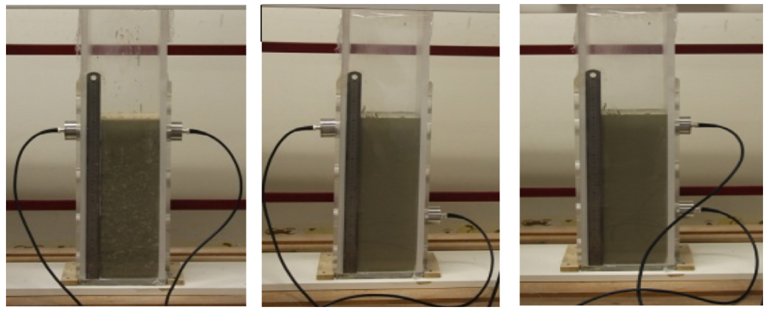


Figure 3 Experimental tool: Sonic auscultation of fresh concrete.

Local crushed sand with a maximum size of 2 mm, fineness modulus was 2.3, specific gravity of 2.65, water absorptions of 0.81% and sand equivalent was 72.5, and gravel with a maximum size of 10 mm, specific gravity of 2.65, water absorptions of 1.4% and Los Angeles coefficient of 22 are used. The particle size distributions of the sand and coarse aggregate are shown in Fig. 2.

2.2. Mixture proportions

The aim of the experimental program is to evaluate the applicability of ultrasonic velocities measurements and to assess the segregation resistance of various SCC mixtures made with fixed sand-to-total aggregate ratio to 0.98, by mass, fixed Water-to-Binder ratio (W/B) of 0.28 and binder content of



(a) Direct mode (b) Semi direct mode (c) Indirect mode

Figure 4 The three transmission modes of ultrasonic velocities measurements.

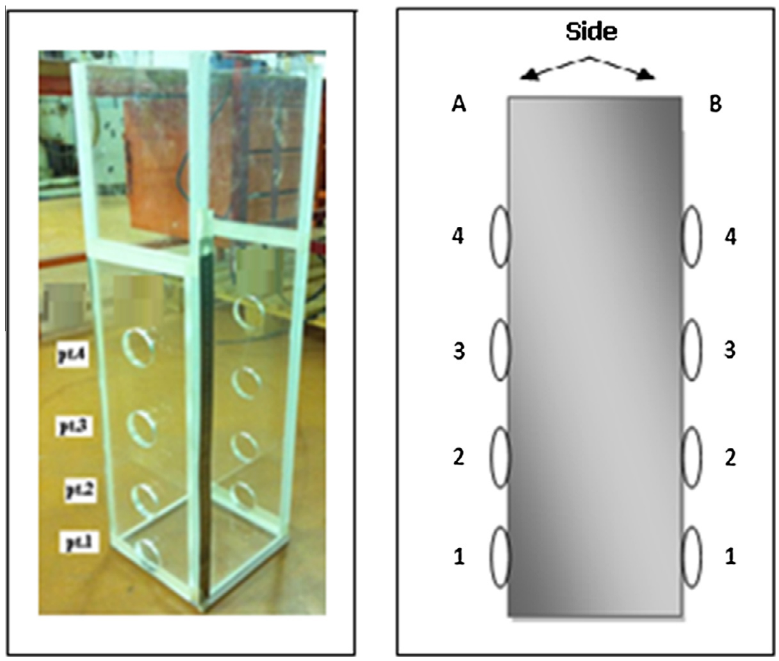


Figure 5 Plexiglas vertical channel used for sonic auscultation of fresh concrete.

Table 3 Rheological characterization and experimental data of stability.

Mixture	Slump flow (cm)	Sieve stability (%)	Strength at 1 day (MPa)	Air content (%)	Visual appreciation
SCC1	50	1.25	25	1.5	+ +
SCC2	72.5	8.8	46	0.9	+ +
SCC3	74	14.8	36	1.3	+
SCC4	75	20	33	0.6	+
SCC5	79	40	24	0.5	±
SCC6	81	43.3	19	0.3	-
SCC7	83.5	51.2	13	0.35	–
SCC8	74	19	36	0.7	+
SCC9	77	24	25	0.5	-
SCC10	79	26	21	0.4	-

Visual appreciation of stability: + + Very good, + good, ± Critique, - Poor, – very bad.

520 kg/m^3. In total, 10 SCC mixtures are designed in order to obtain different fresh-state properties. These 10 mixtures were used to evaluate the sensitivity of ultrasonic velocities measurements to assess the stability of concrete. Stability was adjusted by incorporating the various percentages of SP as well as SF and LF. The compositions of mixtures are presented in Table 2.

2.3. Mixing and preparation of test specimens

The mixing process is kept constant to supply the same homogeneity and uniformity in all mixtures. It starts by mixing all of the aggregates (gravel and sand) and binder for a minute using a standard mixer of 40 l. Then, the mixing water is added and mixed for an additional minute. Thereafter, the SP is added and the concrete is mixed for an additional three minutes.

At the end of mixing, tests are immediately carried out on fresh concrete to assess slump flow diameter, resistance to seg-

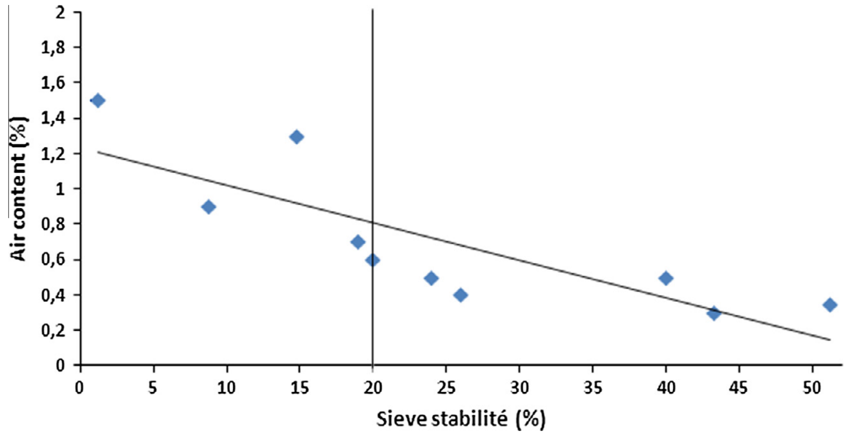


Figure 6 Relationship between the sieve stability test and the air content.

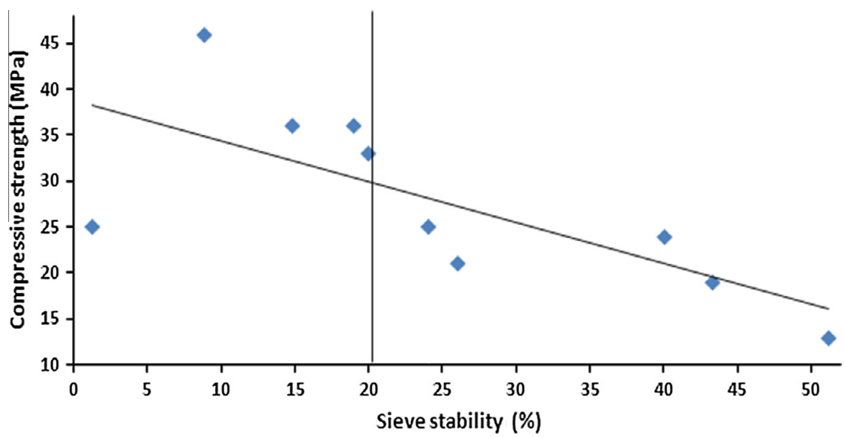


Figure 7 Relationship between the sieve stability test and the compressive strength at 1 day.

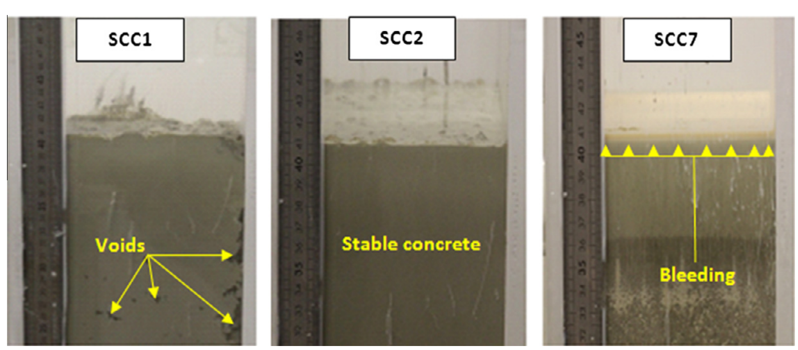


Figure 8 Visual stability.

regation by Sieve segregation test and air content by concrete aerometer test. The tests are performed in accordance with EFNARC [16] standards. The test column used to evaluate segregation resistance is a Plexiglas mold measuring 700 mm in height and 160 × 160 mm in cross section where two transducers are inserted at four heights (Fig. 3).

The 16 × 32 cm cylindrical samples are used to determine the compressive strength after 1 day of hardening.

2.4. Ultrasonic velocity measurements

The measurement principle consists in the determination of propagation time of sound waves through a vertical channel. For this, we use a pair of transducers, one serving as a source (emitter) and the other as a receiver. According to European standard EN 12504-4, we used 3 transmission modes [17–19] (Fig. 4). The system is delivered with a sensor and a nominal

Table 4 Sonic auscultation, depending on time: measurement procedure (m/s).

Mixture	Direct transmission Side A–B					Indirect transmission Side B				Semi-direct transmission
	1–1	2–2	3–3	4–4	σ	1–4	1–3	1–2	σ	2–4
30 min after casting										
SCC1	1132	877	1008	871	**123.99**	2070	2309	3472	**750.03**	1424
SCC2	877	876	870	873	**3.16**	2583	2570	2585	**8.14**	1163
SCC3	862	873	875	858	**8.29**	2120	2145	2140	**13.23**	1145
SCC4	871	865	853	852	**9.29**	2160	2141	2153	**9.61**	1132
SCC5	1105	1086	890	1670	**335.87**	1920	2960	2816	**563.49**	1053
SCC6	1100	1052	780	1516	**303.96**	1820	2960	3240	**752.15**	1020
SCC7	1114	769	1047	1449	**279.44**	1694	1503	2469	**511.58**	1081
SCC8	865	864	848	852	**8.54**	2160	2135	2150	**12.58**	1098
SCC9	1020	865	902	858	**75.03**	2020	1241	3053	**908.96**	1002
SCC10	1008	908	1002	1250	**146.03**	1850	1212	3062	**939.72**	1520
60 min after casting										
SCC1	1164	882	871	872	**144.59**	2083	2162	3125	**580.14**	1413
SCC2	874	873	868	869	**2.94**	2577	2563	2586	**11.59**	1164
SCC3	870	863	875	868	**4.97**	2140	2155	2148	**7.51**	1136
SCC4	868	860	863	877	**7.44**	2150	2148	2155	**3.61**	1126
SCC5	1210	1912	798	1470	**467.09**	1828	2660	2915	**568.45**	1002
SCC6	1112	1825	888	911	**439.02**	2142	3020	1622	**706.60**	1136
SCC7	1056	1134	1093	1458	**184.60**	1800	1801	2967	**673.48**	1626
SCC8	860	874	879	873	**8.10**	2163	2155	2148	**7.51**	1088
SCC9	1125	888	1202	958	**145.21**	2220	1985	2893	**471.28**	1125
SCC10	1212	1019	879	1850	**428.97**	2150	2518	2086	**233.15**	1257
90 min after casting										
SCC1	995	860	876	890	**61.08**	1602	1484	2688	**663.69**	1057
SCC2	873	872	872	867	**2.71**	2573	2560	2580	**10.15**	1177
SCC3	865	858	871	878	**8.52**	2136	2148	2162	**13.01**	1152
SCC4	860	865	880	874	**8.96**	2130	2148	2135	**9.29**	1144
SCC5	1312	1854	828	1270	**420.21**	1928	3160	1826	**742.49**	1252
SCC6	1052	1862	1216	905	**421.75**	2014	1890	2980	**596.75**	1308
SCC7	1199	1515	1471	1596	**172.14**	2233	2567	3436	**621.01**	1749
SCC8	858	870	878	863	**8.69**	2173	2168	2152	**10.97**	1108
SCC9	1312	986	1422	867	**262.79**	2102	1885	3092	**643.43**	1205
SCC10	1802	1288	978	950	**395.83**	2088	2115	1186	**528.74**	1037
120 min after casting										
SCC1	998	870	890	902	**56.89**	1590	1460	2644	**649.32**	1098
SCC2	870	865	872	866	**3.30**	2587	2580	2564	**11.79**	1183
SCC3	868	862	882	882	**10.12**	2142	2152	2170	**14.19**	1163
SCC4	866	862	870	878	**6.83**	2142	2148	2135	**6.51**	1124
SCC5	1845	1044	928	1370	**410.61**	1228	2188	1527	**491.24**	1082
SCC6	1520	896	985	1302	**288.15**	1580	2850	1210	**860.17**	1836
SCC7	1102	1500	1445	1580	**210.59**	2238	2430	3120	**463.84**	1805
SCC8	856	868	876	858	**9.29**	2164	2188	2166	**13.32**	1122
SCC9	1218	886	1222	886	**192.84**	2082	1988	2132	**73.11**	1005
SCC10	1715	1082	878	1050	**366.94**	2178	2524	1146	**716.89**	1147
150 min after casting										
SCC1	1010	875	842	865	**75.93**	1582	1401	2624	**660.08**	1113
SCC2	873	870	872	864	**4.03**	2587	2578	2559	**14.29**	1160
SCC3	874	872	888	868	**8.70**	2152	2165	2176	**12.01**	1180
SCC4	868	866	885	884	**10.14**	2154	2158	2175	**11.15**	1148
SCC5	912	1145	1024	1288	**161.50**	1028	2878	3128	**1147.10**	1182
SCC6	998	1254	2014	1632	**444.05**	1680	1890	3052	**739.00**	1325
SCC7	1004	1478	1431	1536	**242.66**	2248	2249	2949	**404.43**	1905
SCC8	866	878	880	864	**8.16**	2172	2192	2178	**10.26**	1130
SCC9	1298	1084	1812	986	**368.47**	2172	1238	3035	**898.73**	1185
SCC10	1005	1182	988	1380	**183.20**	2268	2724	1246	**756.85**	1087
180 min after casting										
SCC1	1211	1248	1137	1221	**47.48**	1643	2244	2457	**422.13**	1281
SCC2	872	877	871	873	**2.63**	2595	2588	2576	**9.61**	1171

Table 4 (*continued*)

Mixture	Direct transmission Side A–B					Indirect transmission Side B				Semi-direct transmission
	1–1	2–2	3–3	4–4	σ	1–4	1–3	1–2	σ	2–4
SCC3	878	888	898	887	**8.18**	2170	2183	2190	**10.15**	1205
SCC4	860	864	878	880	**9.98**	2146	2143	2162	**10.21**	1134
SCC5	1012	1225	984	1278	**148.39**	1127	1868	2223	**559.21**	1052
SCC6	1680	1312	986	1202	**290.20**	1850	3062	2114	**637.36**	1268
SCC7	1151	1289	1677	1553	**240.30**	2242	2162	2487	**169.34**	1744
SCC8	868	888	878	874	**8.41**	2162	2180	2164	**9.87**	1118
SCC9	1108	1244	912	1084	**136.29**	2078	1838	2338	**250.07**	1275
SCC10	989	1044	1215	890	**136.16**	2389	1708	3142	**717.30**	1005

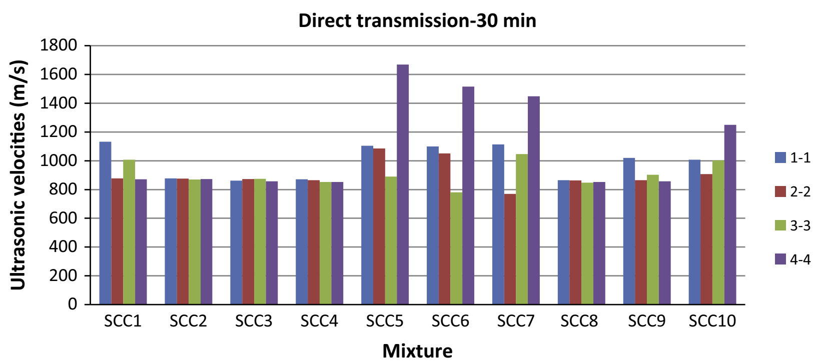


Figure 9 Ultrasonic velocities of various SCCs: direct transmission at 30 min after casting.

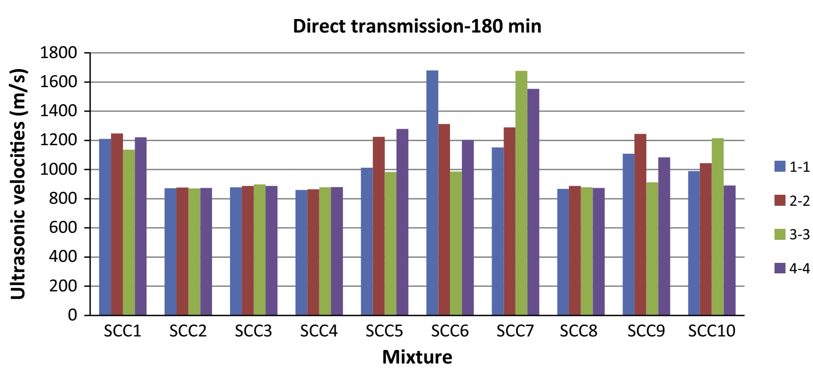


Figure 10 Ultrasonic velocities of various SCCs: direct transmission at 180 min after casting.

frequency transmitter of 54 kHz, either the industry standard. This nominal frequency limits the depth of propagation and the minimum thickness of concrete that can be probed.

After a travel distance "L" and a propagation time "t" in the material, the wave reaches the second transducer. Thus, it is possible to determine the propagation velocity of sound wave in the material: $V = L/t$.

To fill the vertical channel, we used a standard V-Funnel (Fig. 3). To take into account the total heterogeneity of the material tested, the measurements of ultrasonic velocity are carried out on 4 points as shown in the following figure (Fig. 5).

The results of ultrasonic pulse velocity can be used to check the concrete homogeneity and to control the quality of concrete products.

3. Test results and discussion

The results of empirical tests and visual appreciation are given in Table 3.

According to the recommendations of EFNARC [16], a self-compacting concrete should present both a slump flow greater than or equal to 60 cm and a sieve stability less than 15%. When sieve stability is between 15% and 30%, the stabil-

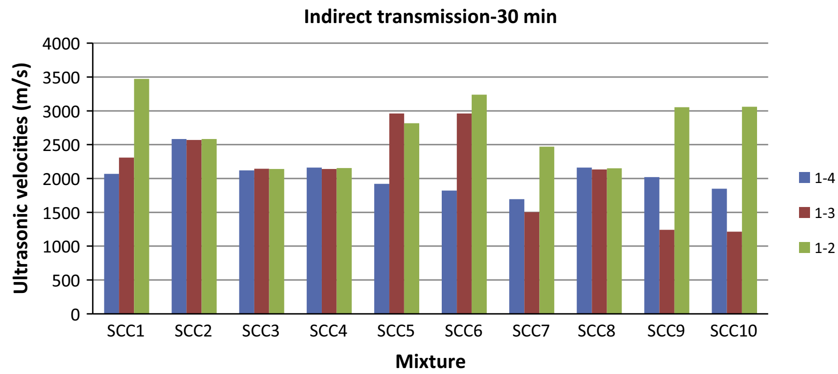


Figure 11 Ultrasonic velocities of various SCCs: indirect transmission at 30 min after casting.

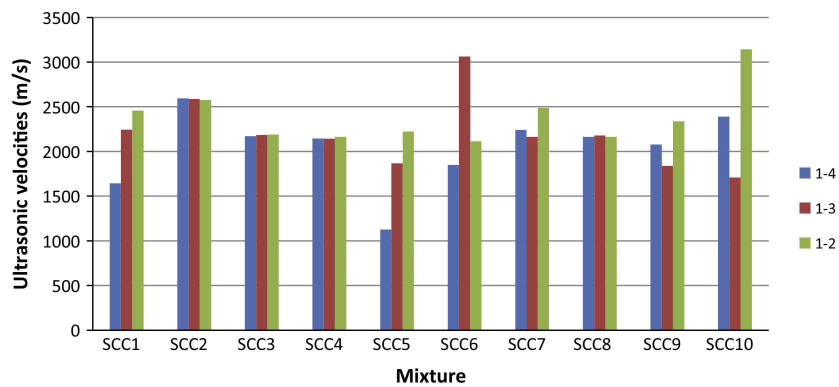


Figure 12 Ultrasonic velocities of various SCCs: indirect transmission at 180 min after casting.

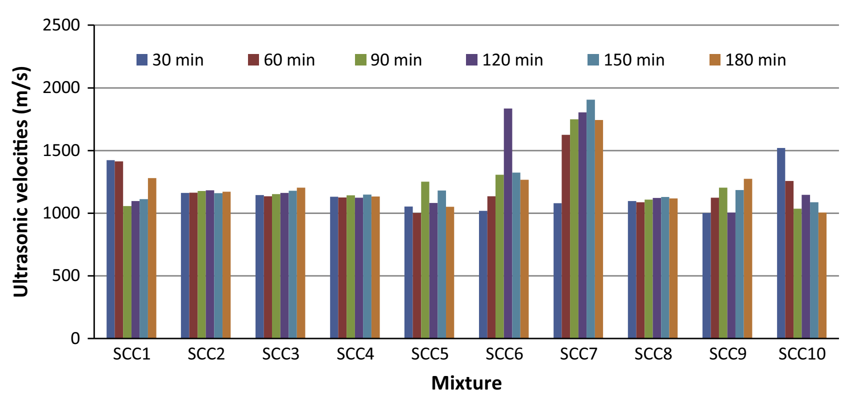


Figure 13 Ultrasonic velocities of various SCCs depending on time after casting: semi-direct transmission.

ity is considered critical and the specific tests of segregation will be necessary [16,20].

First, all the concretes studied have a slump flow higher than 60 cm (except SCC1). Thus, these concretes present an acceptable fluidity with no blockage risk. Therefore, the essential point to be verified for all these concretes is the static segregation (sieve stability test).

The visual appreciation in terms of stability, bleeding and segregation of our concretes in different tests, reveals a good stability of concretes whose value of sieve stability is less than or equal to 20%.

By analyzing the results presented in Table 3, we can note that the instability risk becomes important when the slump flow exceeds 75 cm. In this case, we can admit that it is not necessary to carry out the tests for the determination of resistance to segregation.

Table 3 shows that the concretes SCC1, SCC2, SCC3, SCC4 and SCC8 have a resistance to segregation less than 20%. These concretes are stable compared with other concretes.

In addition, the air content is a parameter that influences the bleeding of concrete. More a mixture contains a large air volume, less it is viscous. Indeed, the volume of paste available

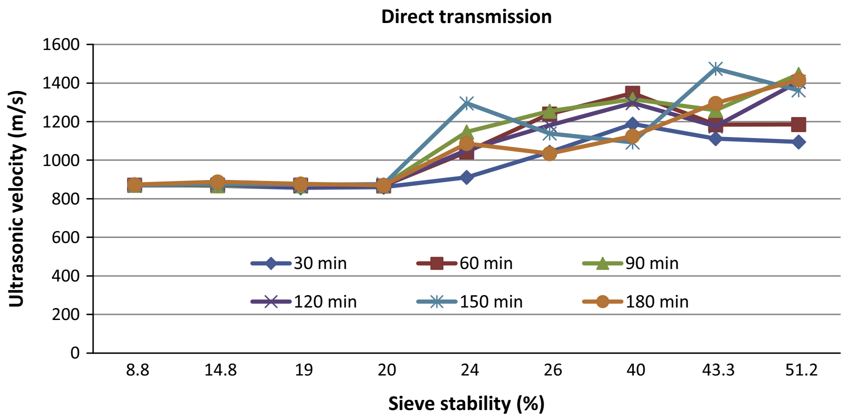


Figure 14 Ultrasonic velocities of various SCCs depending on sieve stability.

to improve flow a mixture also depends on the air content [21]. Therefore, SCC which contains a value of air entrained higher than 0.6%, is of a very weak viscosity compared with other mixtures and it represents a very important stability (less than or equal to 20%).

By analyzing the results presented in Fig. 6, we can note that the instability risk increases when the air content decreases.

As regards the compressive strength, at 1 day, we note that when the stability decreases the compressive strength increases (Fig. 7), except for SCC1. This later contains very high air content (1.5%) and a slump flow of about 50 cm (non-self-compacting concrete), and the resistance becomes therefore very low. Fig. 8 shows the presence of voids in the case of SCC1.

On the basis of the empirical test results and visual appreciation of stability, we can conclude that the concretes SCC2, SCC3, SCC4 and SCC8 represent a very satisfactory stability compared to other concretes.

To confirm this stability conclusion and to validate the proposed approach (ultrasonic velocity on fresh concrete), ultrasonic velocity measurements and its standard deviation σ applied on all SCCs are summarized in Table 4.

The velocity variation measurements are carried out every half hour, until three hours after the casting phase.

Table 4 shows that, at 30 min after casting, the ultrasonic velocity remains almost constant in the case of SCC2, SCC3, SCC4 and SCC8. The variation between their values does not exceed 20 m/s and 25 m/s for direct and indirect transmission mode, respectively. For these concretes, standard deviation σ does not exceed 10 m/s and 14 m/s for direct and indirect transmission mode, respectively. For other concretes, the variation of velocity values exceeds, in some cases, 700 m/s and 1800 m/s for direct and indirect transmission mode, respectively. In some cases, standard deviation σ exceeds 300 m/s and 900 m/s for direct and indirect transmission mode, respectively.

In general, Table 4 also shows that the SCC2, SCC3, SCC4 and SCC8 have values of ultrasonic velocity almost constant regardless of the transmission mode used and the auscultation time after the casting phase. For these concretes, standard deviation σ does not exceed 11 m/s and 15 m/s for direct and indirect transmission mode, respectively.

From Table 4 and Figs. 9–13, we can conclude that SCC2, SCC3, SCC4 and SCC8 present a satisfactory stability compared with other concretes.

In direct transmission mode, the concretes SCC2, SCC3, SCC4, and SCC8 are very stable compared with other concretes. Regardless of the measuring point and time of auscultation, the ultrasonic velocities of these concretes remain almost constant.

In indirect transmission mode, the concretes SCC2, SCC3, SCC4, and SCC8 are very stable compared with other concretes. Regardless of the measuring point and time of auscultation, the ultrasonic velocities of these concretes remain almost constant.

By analyzing the results presented in Figs. 9–13, it is possible to make qualitative comparisons, based on homogeneity

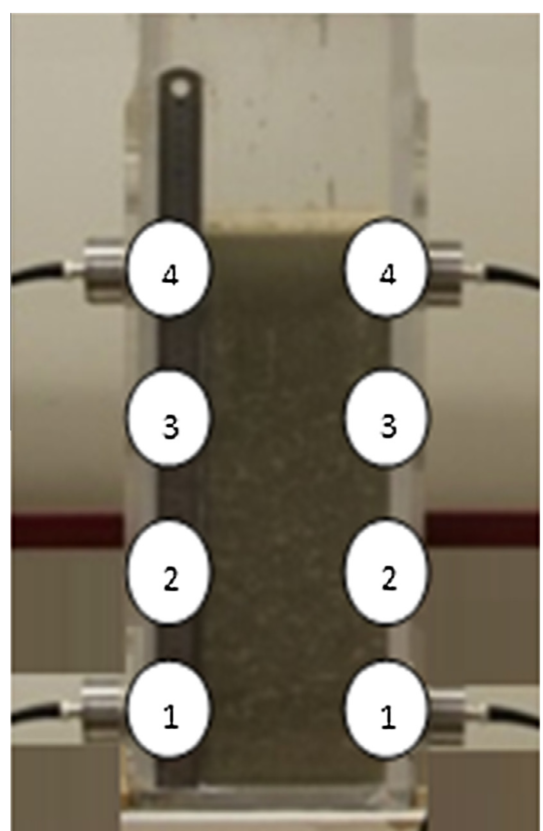


Figure 15 Velocity propagation in side [1–1] and [4–4]: direct transmission mode.

Table 5 Homogeneity coefficient of various SCCs depending on time after casting.

Mixture	Homogeneity coefficient Hc for direct transmission mode					
	30 min after casting	60 min after casting	90 min after casting	120 min after casting	150 min after casting	180 min after casting
SCC1	1.30	1.33	1.12	1.11	1.17	0.99
SCC2	**1.00**	**1.01**	**1.01**	**1.00**	**1.01**	**1.00**
SCC3	**1.00**	**1.00**	**0.99**	**0.98**	**1.01**	**0.99**
SCC4	**1.02**	**0.99**	**0.98**	**0.99**	**0.98**	**0.98**
SCC5	0.66	0.82	1.03	1.35	0.71	0.79
SCC6	0.73	1.22	1.16	1.17	0.61	1.40
SCC7	0.77	0.72	0.75	0.70	0.65	0.74
SCC8	**1.02**	**0.99**	**0.99**	**1.00**	**1.00**	**0.99**
SCC9	1.19	1.17	1.51	1.37	1.32	1.02
SCC10	0.81	0.66	1.90	1.63	0.73	1.11

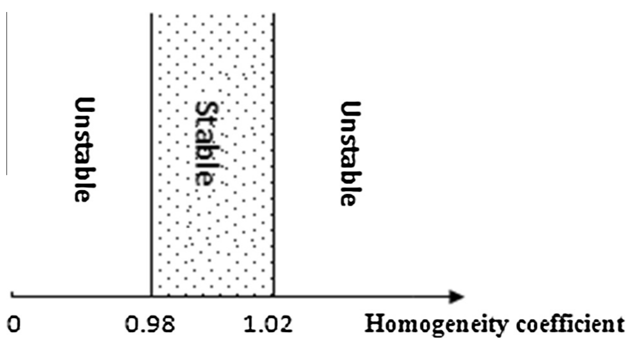


Figure 16 Correlation between stability and homogeneity coefficient.

and quality study, between concretes by means of ultrasonic velocity at fresh state. For the same concrete type, the results obtained, during our work, allow to verify the evolution of ultrasonic velocity depending on time.

At a given time, we can also note that the instability risk of concrete is manifested during the evolution of its ultrasonic velocity. The concretes SCC2, SCC3, SCC4, and SCC8 are very stable compared with other concretes. Regardless of the measuring point, time of auscultation and mode of transmission used, the ultrasonic velocities of these concretes remain almost constant.

The results found by this approach and those found by empirical tests (Table 3) are similar. Both methods confirm the instability of SCC1, SCC5, SCC6, SCC7, SCC9 and SCC10 with regard to the segregation.

Subsequently, we studied, for direct transmission mode, the evolution of sieve stability depending on the ultrasonic velocity (Fig. 14). For each concrete, the values of velocity is represented by the average of the Side A–B: [side 1–1 + side 2–2 + side 3–3 + side 4–4]/4.

Fig. 14 shows that the ultrasonic velocity remains almost constant when the sieve stability does not exceed 20%. Beyond this limit of stability, ultrasonic velocity varies in an arbitrary manner.

For direct transmission mode, in order to quantify the stability of concrete for the vertical channel, a homogeneity coefficient (Hc) is employed as follows:

$$\mathrm{Hc} = \frac{U[\text{side 1–1}]}{U[\text{side 4–4}]}$$

where U[side 1–1] and U[side 4–4] represent propagation velocity in the [1–1] and [4–4] zone, respectively (Fig. 15).

Table 5 summarizes the Homogeneity coefficient of the various SCC mixtures evaluated from the ultrasonic velocity.

The concretes SCC2, SCC3, SCC4, and SCC8 represent a coefficient equal to 1 ± 0.2. Consequently, concrete mixtures with homogeneity coefficient between 0.98 and 1.02, and lower than 0.98 or higher than 1.02 can be considered to have high and low stability, respectively (Fig. 16).

4. Conclusion

Segregation is the separation of the constituent materials of fresh concrete that can occur whenever it is implemented or under the effect of gravity at rest. In these cases, the sonic auscultation on fresh concrete can be used to check the homogeneity of concrete and to control its quality. The results show the effectiveness of the proposed approach.

In this study we found that the concretes SCC2, SCC3, SCC4, and SCC8 are very stable compared with others. Regardless of the measuring point, time of auscultation and mode of transmission used, the ultrasonic velocities of these concretes remain almost constant. The results found by ultrasonic velocity and those found by empirical tests are similar.

In the laboratory, instead of using all empirical tests, we can use ultrasonic velocity to evaluate the static stability of self-compacting concrete.

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